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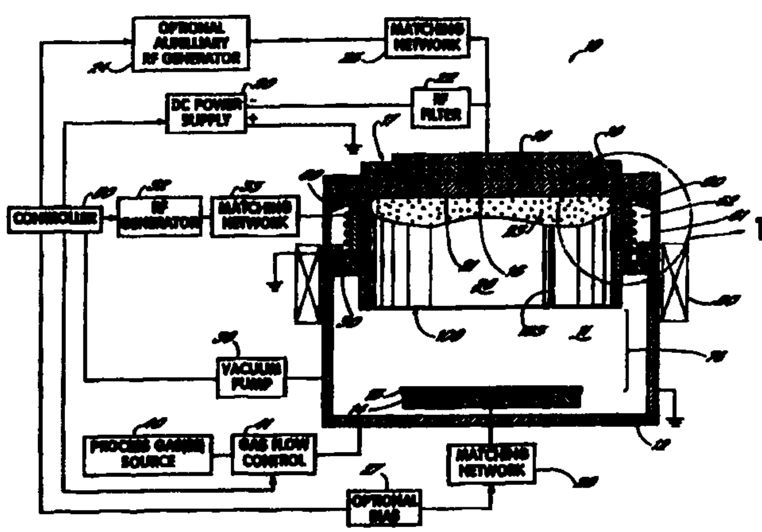
(54) Title: METHOD AND APPARATUS FOR IONIZED SPUTTERING OF MATERIALS

(57) Abstract



An ionized physical vapor deposition apparatus (10, 10a, 10b) is provided with an RF element, preferably a helical coil (30), that surrounds space (11) within a vacuum chamber (12) between a target (16) and a substrate holder (14). RF energy, preferably at about 2 MHz or elsewhere in the 0.1 to 60 MHz range, is coupled into the space to form a secondary plasma (29) in a volume (26) of the space between the substrate holder and the main plasma that is adjacent the target. The secondary plasma ionizes sputtered material which is then attracted toward a substrate (15) on the support by a bias on the substrate and/or by an axial magnetic field to impart directionality to the moving ionized sputtered particles to render them perpendicular to the substrate at incidence, so as to coat the bottoms of narrow high aspect ratio features on the substrate. A window (60) of dielectric material such as quartz, either in the wall of the chamber or inside the chamber, or insulation (86) on the coil, protects the coil from adverse interaction with plasma. Shields (100, 200, 300) between the space and the dielectric material prevent sputtered particles coating the dielectric material. The shields are partitioned or slotted to prevent induced currents in the shields. The shields may be biased to control contamination and may be commonly or individually biased to optimize the uniformity of coating on the substrate and the directionality of the flux of ionized material at the substrate. The shield may be formed of a plurality of angled segments (302) that are spaced to facilitate communication of a secondary RF plasma from adjacent the window to the volume of the chamber where the sputtered material is ionized, with the sections angled and spaced to shadow at least most of the target from the window. Alternatively, electrically conductive shield (100) may be provided in close proximity to the window or insulation, preferably spaced therefrom less than the mean free path of gas atoms in the chamber, so that plasma will not form behind the shield. The shield (100) has at least one axial slit (103) therein to prevent azimuthal or circumferential currents from shorting the coupled energy.

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METHOD AND APPARATUS FOR IONIZED SPUTTERING OF MATERIALS

This invention relates to sputter coating, and more particularly, to a method and an apparatus for conducting Ionized Physical Vapor Deposition (IPVD) of coating material onto substrates.

Background of the Invention:

The existence of sub-micron high aspect ratio features, such as vias, trenches and contact holes, in semiconductor manufacturing presents a variety of coating problems. In the manufacture of Very and Ultra Large Scale Integration (VLSI and ULSI)) semiconductor devices, contacts on the bottoms of such features often must be coated with liners, and the features often must be filled with conductive metals. In many semiconductor device manufacturing situations where films are to be deposited, it is either required or at least preferred to apply the coatings using a physical vapor deposition (PVD) process. The deposition of films on the bottoms of narrow high aspect ratio features (apertures) by physical methods requires the achievement of a high degree of directionality in movement of the material to be deposited toward the substrate. Higher aspect ratio features require greater directionality. To effectively coat contacts, for example, on the bottoms of narrow high aspect ratio holes on the surface of a substrate, it is necessary for the particles of coating material to move at angles to the normal that are not substantially larger than the angular openings of the features.

In semiconductor device manufacture, for example, it is necessary to metallize contacts at the bottoms of high aspect ratio holes and trenches that may be in the range of 0.25 to 0.35 microns in width, and that are likely to become narrower as the trend toward device miniaturization continues. Metallizing such contacts by a physical deposition process, such as sputter coating, is desirable because PVD processes present technical and commercial advantages over alternative processes in film purity achieved, in throughput, and in the overall cost and simplicity of processing equipment. For example, chemical vapor deposition (CVD) processes are sometimes used for the deposition of films in deep holes and trenches due to the ability of the chemical process to form the film at the surface of the substrate inside of the holes or trenches. CVD processes, however, require equipment that is more complex and expensive than PVD process equipment. The CVD processes, due to their chemical nature, often involve environmental factors and employ chemical precursors that can provide a source of device contamination, and typically these systems require higher frequencies of preventive maintenance resulting in non-productive down time. For many types of films, PVD processes are faster than CVD processes, yielding better throughput and therefore lower cost. In addition, CVD processes might not exist or may not be practical for many deposition materials, such as by requiring complex precursors and delivery systems which may preclude the CVD deposition. Acceptable manufacturing CVD processes exist for titanium, titanium

nitride, and tungsten. However, CVD processes for aluminum, copper, tantalum, and tantalum nitride either do not exist or if they exist, they are immature or not commercially viable. In addition, with some processes, CVD can subject devices that are partially formed on the substrates to heat for prolonged periods, which can cause migration and diffusion of material at material boundaries or can subject the devices to other heat induced damage or exceed the thermal budget for the process in question.

Because of the decreasing sizes and increasing aspect ratios of features, the preferability of applying coatings by physical vapor deposition in certain applications has increased demands on the sputtering process to achieve higher and higher degrees of directionality in the movement of the coating materials onto the substrates. Unless the paths of the particles of sputtered material incident onto the substrate can be maintained highly parallel and normal to the plane of the substrate surface, attempts to sputter coat high aspect ratio features will result in excessive deposits on the upper sides of the features or a closing of the mouth of a feature, in which event the physical deposition process will not achieve results that are satisfactory.

A sputter coating process is typically carried out by placing a substrate and a target of high purity coating material into a vacuum chamber filled with an inert gas such as argon and creating a plasma in the gas. The plasma is typically generated by maintaining the target, either constantly or intermittently, at a negative potential, so that the target functions as a cathode to supply electrons that excite the gas in the chamber and form a plasma adjacent the target surface. The plasma generation is usually enhanced with a magnetron cathode assembly in which magnets behind the target trap these electrons over the surface of the target where they collide with atoms of the process gas, stripping electrons from atoms of gas and converting them into positive ions. The gas ions are accelerated toward the negatively charged target where they collide with the surface and eject from the target surface atoms and atomic clusters or particles of target material and secondary electrons. The secondary electrons play a major role in sustaining the plasma. The ejected particles of target material are neutral in charge and propagate through the vacuum space in various directions with some striking the substrate, to which they adhere to form the film. Increasingly narrower features and higher aspect ratio features on the substrates act to decrease the acceptance angle of the aperture, thereby shadowing the sides of the features, resulting in increasingly more of the incident particles being intercepted by the sides of, and areas around, the features with increasingly fewer of the particles available to deposit on the feature bottoms.

Various schemes have been used for causing the propagating particles to move in straight lines toward and normal to the substrate surface. One approach involves the use of a physical collimator plate between the target and the substrate to achieve normal distribution of angles of incidence and improve incident particle directionality by intercepting particles directed at low angles to the collimator so that the particles that pass through the collimator are only those that are normal or nearly normal to the substrate. Another approach, known as long-throw sputtering, calls for increasing the target to substrate spacing so that only particles moving normal or close to normal angles to the substrate travel the length of the chamber to strike the substrate. Collimators provide a source of particulate contamination because the intercepted particles are deposited on the collimator, where film builds up and tends to eventually flake off. Both the collimated deposition and long-throw schemes achieve directionality by eliminating material that is moving at low angles to the substrate, which drastically reduces the percentage of the sputtered material incident on the substrate and thereby substantially

decreases the deposition rates. It also increases preventive maintenance, decreases target material utilization, and reduces throughput.

A further method of directing sputtered material that has been given renewed consideration is the process of ionized sputtering, often referred to as Ionized Physical Vapor Deposition or IPVD. With IPVD, coating material is sputtered from a target using magnetron sputtering or other conventional sputtering or evaporation techniques. In sputter coating processes, sputtered particles are emitted from the target at broad angles of emission. IPVD seeks to improve the directionality by ionizing the particles so that they can be electrostatically or electrically steered in a direction normal to the substrate.

In IPVD, additional plasma is created in the gas in the space between the target and the substrate through which the sputtered particles pass on their way to the substrate. In the prior art, the additional plasmas have been formed in the space by various methods, such as by capacitively coupling RF energy into the chamber downstream of the target, or have been formed remote from the space by electron cyclotron resonance (ECR) or other microwave plasma generating techniques and then caused to flow into the space. The particles of sputtered material passing through this space collide with the electrons or metastable neutrals of the ionized process gas. The collisions tend to strip electrons from the atoms of the sputtered particles leaving the particles positively charged. These positive ions of sputtered material are then electrically accelerated toward the substrate, for example, by application of a negative bias to the substrate.

IPVD processes in the prior art indicate a number of drawbacks and problems which preclude their practical use in a manufacturing environment. Such processes have, for example, produced low overall efficiency. In particular, IPVD processes typically yield low deposition rates. Furthermore, the prior art processes have produced high levels of film contamination. In particular, with IPVD proposals of the prior art, the filling of high aspect ratio features has been found to deteriorate as sputtering power at the target increases. Such deterioration has limited the sputtering of aluminum alloys to less than 3 kW of DC power with a 12 inch magnetron target as compared to 12 to 30 kW that is typically achievable for such a target/magnetron assembly. The low sputtering power results in a low deposition rate resulting in low productivity and throughput as well as increased contamination, e.g., 10 to 40 minutes of sputtering time per wafer compared with the typical wafer processing times of about 45 seconds to one minute. Further, the fractional ionization of sputtered material has been found to be low unless the apparatus is operated at a relatively high pressure in the sputtering chamber, such as 20 to 40 mTorr. With argon process gas, this pressure is higher than the desired sputtering pressures that are typically less than 15 mTorr or in the low millitorr range. The higher pressures have had a tendency to reduce the quality of deposited film properties and to increase film contamination. In addition, a higher operating pressure degrades the flat-field uniformity of the process forcing a larger vacuum chamber design which, in turn, reduces the ionization efficiency further. Other problems that have resulted with IPVD processes of the prior art are the undesired sputtering of RF electrodes or elements by the plasmas, the flaking of accumulated sputtered material from the RF elements due to the unwanted deposition thereon, the shorting of RF elements by the plasmas or material that had deposited on the elements, and other plasma and material interactions with the electrode or element used to couple the RF energy into the plasma to ionize the sputtered material.

Accordingly, there is a need for an IPVD apparatus and method that overcomes the drawbacks and problems of the prior art. In particular, there is a need for a practical and effective IPVD apparatus that produces acceptably high overall efficiency, particularly high deposition rates, high sputtered material ionization efficiency and low contamination of the deposited film. There is a particular need for an apparatus that produces a film of high uniformity and quality, while providing productivity sufficiently high for the process to be commercially useful.

Summary of the Invention:

A primary objective of the present invention is to provide a method and apparatus for depositing thin films on the bottoms, and to some extent on the sides, of narrow high aspect ratio holes and trenches in VLSI and ULSI semiconductor wafers. It is also a primary objective of the present invention to provide a method and apparatus for conducting ionized physical vapor deposition that has a high overall efficiency, and particularly, that yields a high deposition rate at a wide range of pressure with a high ionization efficiency of the coating material. It is a further objective of the present invention to provide an effective IPVD method and apparatus that maintains low deposited film contamination. Yet, it is another objective of the present invention to provide an IPVD process and hardware which has low preventive maintenance requirements.

A particular objective of the present invention is to provide an apparatus and method of IPVD that will allow the sputtering power at the target to be sustained at least at a moderate level and that will provide a high RF energy coupling efficiency into sputtered material without the need to maintain the chamber at a relatively high sputtering pressure. A further objective of the present invention is to provide a method and apparatus in which adverse interaction between the plasmas in the chamber and the electrode or element used to couple the RF energy into the plasma to ionize the sputtered material is kept low, particularly the sputtering of, the flaking of sputtered material from, or the potential shorting of the electrode.

According to the principles of the present invention, an IPVD apparatus and method are provided in which a main plasma is formed adjacent to the target to sputter material from the target while an RF element couples energy into the PVD processing chamber to produce a secondary plasma in a volume of the chamber between the main plasma and a substrate. The secondary plasma is supplemental to the main plasma that is typically confined close to the sputtering target. The secondary plasma generally fills the chamber, but primarily occupies at least a portion of the space between the target and the substrate, thereby ionizing the sputtered material particles in flight while they are moving from the target so that the particles can be electrostatically accelerated toward the substrate in the ion-assisted deposition of the sputtered material onto the substrate.

The ionized sputtered material is preferably accelerated toward the substrate by a negative bias applied to the substrate, which may be controlled to provide for optimal steering of the moving ions without damaging the surface of the wafer. Alternatively or in addition, the chamber may be further surrounded with permanent magnets or electromagnets that produce an axial magnetic field in the chamber between the substrate and the target to aid in confining the ionized sputtered particles in paths parallel to the axis of the chamber and normal to the surface of the substrate.

The RF ionization energy coupling element may be an RF electrode, preferably an inductive element, such as, for example, one to a plurality of coils surrounding the chamber. As described in greater detail below,

the RF element may either be positioned within the chamber, preferably insulated from the chamber process gas, or positioned outside of the chamber.

The preferred apparatus is also provided with a protective structure comprising an electrically non-conductive and non-magnetic dielectric material that protects or isolates the RF element from adverse interaction with plasmas in the chamber, such as interaction with the main plasma as well as with the secondary plasma produced by the RF element. Preferably, the protective structure is such that sputtered material that impinges upon it, if any, adheres to the structure in such a way that it does not tend to flake off of the structure to result in a source of contamination. The parts of the protective structure are further preferably configured to prevent eddy currents therein or in layers of sputtered material deposited thereon and to prevent electrostatic shielding of the RF element.

Various configurations of the RF element and protective structure are possible within the limits of this invention. For example, in one embodiment, an RF coil surrounds the chamber behind the protective structure, which forms part of the vacuum tight inner wall of the chamber surrounding the processing space, with the RF coil covered with an external conductive enclosure. Alternatively, the RF coil is within the vacuum of the processing chamber outside of and downstream of the target periphery, with the protective structure separating the RF coil from interaction with the plasmas. In a further embodiment, an RF coil is provided that is covered with protective insulating material, either with a solid insulator that completely covers the coil conductor or with a slotted or segmented insulator having slots sufficiently narrow to discourage the formation of plasma adjacent the conductor. The RF coil and protective structure are preferably cylindrical in shape and surround the processing space.

The preferred apparatus further includes a shield array provided to shield the protective structure so that the function of the protective structure is not compromised by the effects of sputtered material deposition thereon. Various embodiments of a protective structure and shield array may be utilized, as described in the following examples.

First Embodiment

In this embodiment, the RF element comprises a helical coil surrounding the chamber from behind a mostly cylindrical quartz window utilized as the protective structure. The mostly cylindrical quartz window may form part of the vacuum tight inner wall of the chamber, or it may be in the form of an insulator encasing the coil inside of the chamber, or in some other form that isolates the coil conductor from the process gas.

A substantially cylindrical shield is provided that surrounds the chamber in close proximity to the window that separates the coil from a PVD processing chamber. The shield is slit preferably in a direction parallel to its axis of the chamber. By "close proximity" is meant spaced from the window a distance that is sufficiently short as to prevent the formation of plasma between the shield and the window. The slit shield follows the shape of the dielectric window that separates the coil from the vacuum chamber and process gas. The shield prevents the deposit of coating material onto the window. When the material is electrically conductive, electrical short circuiting of the coil could occur preventing RF energy from being transmitted into the chamber. The shield is preferably slit in such a way as to prevent the shield itself from providing a circumferential path around the chamber in which circumferential currents could be induced, which would consume energy from the RF coil and detract from the efficiency of energy coupled into the supplemental

plasma. The shield is further extended sufficiently far in an axial direction to short axial electrical fields across the RF coil and thereby optimizing the efficiency of the inductive coupling of energy into the plasma and reducing capacitive components of the coupled energy. In addition, the shield is maintained in close spaced proximity to the window so as to prevent generation of plasma behind the shield so that the plasma is more efficiently generated in the space through which the sputtered particles travel. Preferably, this spacing of the shield from the window is not greater than the mean free path of atoms of the process gas or the minimum diffusion length of the plasma in the space.

The slit in the shield is sufficiently wide to allow the formation of plasma therein, so that the plasma will continually remove by resputtering any deposition of coating material on the window as a result of material from the source passing through the slit.

The location and configuration of the shield relative to the protective covering of the coil contributes to a high efficiency of plasma generation in the space of the chamber, avoiding losses due to the generation of plasma between the shield and the coil. As a result, a high ionization efficiency of the sputtered material is provided.

With this embodiment, plasma generation in ineffective areas of the chamber, such as between shield structure and the coil-protecting insulator or window, is prevented, and the loss of ionization efficiency thereby is avoided.

Second Embodiment

In this embodiment, an enclosure, a dielectric window and solid or segmented insulation is used, alone or in combination, to mutually protect the RF element from the plasmas and the sputtered material. The shield array is preferably in the form of a plurality of shield sections, which may be biased to control the sputtering thereof by the plasmas. The shield array has a plurality of gaps to at least partially electrically interrupt the shield sections to prevent induced eddy currents from consuming the energy and countering the coupling of energy to the plasma. Further, the individual shield sections are preferably electrically separate so that they may be individually biased to optimize the uniformity of coating on, and the directionality of ionized material onto, the substrate. Spaces between the shield segments facilitate the propagation of plasma from behind the shield into the processing space.

Third Embodiment

In this embodiment, a helical coil surrounds the chamber behind a protective structure. So arranged, the coil is protected from contact with the plasmas formed within the chamber. An array of shield sections is provided within the chamber, also surrounding the space between the target and substrate, and preferably biased to control the sputtering thereof by the plasmas. The shield array has a plurality of gaps to at least partially electrically separate the shield sections, in part to prevent induced eddy currents from consuming the energy and countering the coupling of energy to the plasma. The shield sections are configured and oriented, and the gaps are defined, so that the shield sections shadow the protective structure from the target while minimally affecting the coupling of energy from the coil and the formation and location of the secondary plasma.

The shield array is situated relative to the protective structure so that coating does not build up on it that would support eddy currents therein or that would produce electrostatic shielding of the RF coil. Preferably, no part of the target is visible from any part of the protective structure, and if any part of the

protective structure can see the target so as to accumulate a coating of conductive sputtering material, the coated area would not be so shaped as to allow it to support eddy currents or cause a significant shielding of the coil.

In the illustrated examples of this third embodiment, the protective structure comprises a dielectric window. The shield array is formed of angled sections that collectively entirely block all paths between the target and the window. The sections are also angled so that much of the volume of the space between the main plasma and the substrate is visible from the coil. As such, the window is protected from sputter deposition from the target while providing the greatest effective coupling of energy to form the secondary plasma for ionizing the sputtered material. The shield sections are preferably spaced from the window and have sufficient space between adjacent sections to allow some part of the coil to be in sight of the volume of the chamber where the secondary plasma is desired to be formed, so that plasma can be formed adjacent the window and extend into the volume where sputtered material can be ionized.

According to one illustrated example of this third embodiment, the shield array is formed of a plurality of axially spaced frusto-conical sections positioned inside of the window and inclined at an angle generally perpendicular to a path from the target to the window. The shield sections may be inclined at the same angle relative to the axis of the chamber or with the sections inclined at different angles, for example, with the sections at greater distances from the target at smaller angles to the axis. Preferably, the sections do not shadow adjacent sections from every point on the target, although a minimal overlap may tend to reduce scattered sputtered particles from striking the window. The shield sections are preferably further segmented circumferentially by gaps in the sections, thereby interrupting potential induced current paths.

According to a further illustrated example of this third embodiment, the shield array is formed of a plurality of flat or slightly curved axially extending rectangular blades circumferentially spaced around the chamber inside of the window. These sections are spaced from the window, and are each inclined at an angle relative to the radius of the chamber to collectively shadow the window, or at least the portion of the window substantially within the field of the coil, from the entire area of the target, but to allow some part of the coil to be in sight of the volume of the chamber where the secondary plasma is desired to be formed. In this way a secondary plasma can form adjacent the window and readily extend into the volume through which sputtered particles will pass. The shield sections of this embodiment are preferably inclined at the same angle relative to the radii of the chamber. Preferably, the sections do not shadow adjacent sections from every point on the target, although a minimal overlap may be effective to further reduce coating of the window. The shield sections are preferably circumferentially spaced from each other and spaced from the target and the substrate by a distance equal to at least the mean free path of molecules in the gas in the vacuum chamber.

* * *

When the invention is used in sputtering coating systems, sputtering power can be maintained at a high level, thereby maintaining a high deposition rate and a high sputtered material ionization rate. These results are achieved without the high incidence of problems such as the shorting out the RF coil or increased contamination and thereby the deterioration of the deposited film. As a result, high aspect ratio features can be filled effectively and efficiently by sputtering, with high directionality of incident sputtered material normal to the substrate surface. The need of the prior art systems to reduce sputtering power is eliminated, as a dense sputtering plasma is prevented from shorting out or otherwise adversely affecting the RF plasma coupling element that creates the

plasma that ionizes the sputtered material. The plasma produced by the RF element itself is prevented from shorting out the element. Sputtering gas pressure may be kept at low or normal sputtering levels, and loss of directionality due to scattering is prevented. Adverse affects from sputtering of the RF coupling element are avoided. These advantages are achievable in processing times that are comparable to conventional sputtering methods that do not provide the quality high aspect ratio feature coating that the present invention affords.

In addition to enhancing PVD processes, particularly sputter coating processes when used for depositing coatings into high aspect ratio features, the present invention also provides advantages in PVD processes that employ evaporation sources or other sources of vaporized material that are deposited by substantially physical techniques. Reactive processes and physical processes that are enhanced by or otherwise include chemical deposition of the material may also benefit from the present invention. The invention has particular utility in connection with the deposition of metal films, but can also provide advantages in the deposition of other materials, particularly oxides and nitrides.

These and other objectives and advantages of the present invention will be more readily apparent from the following detailed description of the of the preferred embodiments of the invention, in which

Brief Description of the Drawings:

Fig. 1 is an elevational diagrammatic representation of a IPVD sputtering apparatus according to one embodiment of the present invention.

Fig. 1A is an enlarged elevational diagram of a portion of **Fig. 1** illustrating an alternative form of protection for the coil.

Fig. 2 is a perspective diagram of a shield of the apparatus of **Fig. 1**.

Fig. 3 is a diagrammatic representation of a IPVD sputtering apparatus according to one embodiment of the present invention.

Figs. 4A-4D are diagrams illustrating alternative coil configurations of the apparatus of **Fig. 3**.

Fig. 5 is a diagrammatic representation of an IPVD sputtering apparatus having an alternative configuration of the secondary plasma RF coupling element and protective structure in contrast to that shown in **Fig. 3**.

Fig. 6 is a diagrammatic representation of an IPVD sputtering apparatus having another alternative configuration of the secondary plasma RF coupling element and protective structure in contrast to those shown in **Figs. 3** and **5**.

Figs. 7A-7D are diagrammatic representations illustrating forms of coil insulating protective structure in the alternative to that shown in the embodiment of **Fig. 6**.

Fig. 8 is a diagrammatic representation of a IPVD sputtering apparatus according to one embodiment of the present invention.

Fig. 9 is a diagram of a portion of **Fig. 8** illustrating an alternative configuration of a shield array.

Fig. 10 is a cross-sectional view of the shield array embodiment of **Fig. 9** taken along the line 3-3. of **Fig. 9**.

Detailed Description of the Invention:

Fig. 1 diagrammatically illustrates a sputter coating apparatus 10 according to principles of the present invention. The apparatus 10 includes a vacuum tight processing space 11 enclosed in a chamber 12. Mounted in the chamber 11 at one end thereof is a substrate support or susceptor 14 for supporting a semiconductor wafer 15 mounted thereon. The wafer 15, when mounted on the substrate support 14, is parallel to and faces a target 16. The target 16 is formed of a sputter coating material that is to be deposited as a thin film on the wafer 15. The processing space 11 is a generally cylindrical space that is maintained at an ultra high vacuum pressure level and is filled with a processing gas, such as argon, during processing. The space 11 lies in the chamber 12 between the substrate support 14 and the target 16.

The target 16 is part of a cathode assembly 17 mounted in the chamber 12 at an end thereof opposite the substrate support 14. The cathode assembly 17 includes a target holder 18 to which the target 16 is secured. A magnet structure 19 is typically provided behind the target holder 18 on the opposite side thereof from the substrate support 14. A dark space shield 13 may also be provided around the periphery of the target 16. The magnet structure 19 preferably includes magnets that produce a closed magnetic tunnel over surface 21 of the target 16 that traps electrons given off into the chamber 12 by the cathode assembly 17 when it is electrically energized to a negative potential as is familiar to one skilled in the art. The magnet structure 19 may include fixed or rotating or otherwise moving magnets, which may be permanent or electromagnets, of any one of a number of magnetron sputtering assemblies known in the art.

A power supply or source 20 of electrical energy, usually a source of DC power, which may be switched on to remain constant or may be pulsed, is connected between the cathode assembly 17 and the wall of the chamber 12, which is usually grounded and serves as the system anode. The cathode assembly 17 is insulated from the wall of the chamber 12. The power supply 20 is preferably connected to the cathode assembly 17 through an RF filter 22. An auxiliary source of energy such as an RF generator 24 may also be optionally connected to the cathode assembly 17 through a matching network 25. A bias circuit 27 is also provided and connected to the substrate support 14 through a matching network 28. The bias circuit 27 applies a bias to a wafer 15 mounted on the substrate support 14. A bipolar DC supply or an RF supply can be used for this purpose. Power from the steady or pulsed DC power supply 20 and/or RF generator 24 produces a negative potential on the surface 21 which causes electrons to be emitted from surface 21 of the target 16. The emitted electrons remain trapped over the surface 21 by the magnetic field generated by the magnet structure 19 until they strike and ionize atoms of process gas in close proximity to the surface 21 of the target 16, forming a main plasma 23 adjacent to the target surface 21. This main plasma 23 becomes a source of positive ions of gas that are accelerated toward and against the negatively charged surface 21, where they eject particles of coating material from the target 16.

The space 11 between the target surface 21 and the substrate support 14 can be considered as formed of two parts. One part is that primarily occupied by the plasma 23, which is shaped to produce a desired erosion pattern on the sputtering surface 21 of the target 16, while the second part of the space 11 is a remaining volume 26 that lies between the plasma 23 and the substrate 15 on the substrate support 14. The particles of sputtered material from the target 16 generally originate as electrically neutral particles that can propagate only by momentum through the space 11, where some, but not all, pass through the plasma 23 and the volume 26 to

impinge upon the substrate 15. In a conventional sputtering apparatus, neutral sputtered particles passing through the plasma 23 are not ionized significantly since the plasma 23 occupies a small volume near target surface 21, and at operating pressures of interest, few collisions occur between the neutral sputtered particles and particles of the plasma 23. As such, in conventional sputtering, the neutral sputtered particles exit the plasma 23 mostly neutral and stay neutral until deposited as a thin film on substrate 15.

For coating contacts at the bottom of high aspect ratio holes and other features and for metallizing holes by filling them with sputtered conductive material, it is highly preferred in VLSI and ULSI semiconductor device manufacturing that the particles impinge onto the substrate surface in a narrow angular distribution around the normal to the substrate, so that they can proceed directly into the features and onto the feature bottoms, and not strike or be shadowed by the feature sides. This perpendicular impingement of particles onto the substrate is facilitated in the apparatus 10 by ionizing the sputtered particles as they pass through the volume 26, so that the particles develop an electrical charge. Once charged, the particles can be electrostatically accelerated or otherwise electrically or magnetically directed into paths that are parallel to the axis of the chamber and perpendicular to the surface of the substrate 15. Such a process is known in the art as ionized physical vapor deposition (IPVD) or ion-assisted sputter coating.

According to a preferred embodiment of the present invention, in-flight ionization of sputtered particles in the space 26 is carried out by reactively and preferably inductively coupling RF energy into the volume 26 by provision of an RF element that surrounds the volume 26 but does not occupy the space 11. The RF element is preferably in the form of a helical coil assembly 30, though coil configurations other than helical may be used. Examples of possible configurations 30a-30d of coil assemblies are illustrated in Figs. 4A-4D. Furthermore, the configurations of the coil assembly 30 should include coils, windings and/or coil and winding arrangements. In addition, it is possible to feed RF energy into a coil in manners different than what is shown, for example, by adding a center RF tap to the center of the coil and grounding the other two leads or vice versa. The coil assembly 30 inductively couples energy into the process gas in the volume 26 thereby forming a secondary plasma 29 that generally fills the volume 26 and is distinct from the main plasma 23. An RF generator 32, preferably operative in, but not limited to, the range of from 0.1 or 0.2 MHz to 60 or 80 MHz, is connected to the coil assembly 30 through a matching network 33 to provide the energy to the coil assembly 30 to form the secondary plasma 29 in the volume 26.

A source of processing gas 40 is connected to the chamber 11, through a flow control device 41. For sputter processing, the supply gas 40 is typically an inert gas such as argon. For reactive processes, additional gases such as nitrogen and oxygen can be introduced through auxiliary flow controllers. A high vacuum pump 39 is also connected to the chamber 12 to pump the chamber 12 to a vacuum level in the milli Torr or sub-milli Torr range. Pressures in the 5 to 50 milli Torr range are preferred. The pump 39 maintains the ultra high vacuum with a flow rate of process gas in a range of 5 to 300 standard cubic centimeters per second (sccm). The apparatus 10 also includes a main controller 50 that is preferably a microprocessor-based programmable controller operative to sequence and control the operation of the components discussed above. The controller 50 has outputs for controlling the energization of the cathode power supplies 20 and 24, the substrate bias power supply 27, the RF generator 32 for energizing the secondary plasma generating element that is the coil assembly 30, the gas flow control 41, the pump 39 and other controllable components of the apparatus 10.

In order to achieve directionality of the ionized sputtered particles, an electrical potential gradient may be maintained in the plasma sheath in front of substrate support 14 by negatively biasing the substrate 15 relative to the secondary plasma 29 with a bias power supply 27 connected to the substrate support 14 through a matching network 28, to provide force to accelerate the positively ionized sputtered particles toward and onto the substrate surface. A bipolar DC supply or an RF supply can be used for this purpose.

In addition or in the alternative, a magnet 80 may be provided around the chamber 12 to produce a magnetic field in the axial direction in the chamber 12. The magnet 80 may be an electromagnet or formed of one or more permanent magnets. The fields from the magnet 80 cause the charged particles to gyrate about the lines, thereby increasing their confinement in the radial direction. In the presence of an axial electric field, the charged particles can be directed in the axial direction, moving toward the substrate and minimizing radial losses.

Between the coil assembly 30 and the space 11 there is provided a protective structure that prevents the plasmas 23 and 29 from contacting and electrically interacting with the coil assembly 30. This structure is an electrically non-conductive material that does not impede the magnetic field surrounding the coil assembly 30 from reaching into the volume 26. One preferred form of protective structure is that of a window 60, made of a vacuum-compatible dielectric material such as quartz, in the wall of the chamber 12, that is mounted to form a vacuum-tight seal with the chamber wall. The window 60 may be a single piece of electrically-insulating and magnetically-transparent material or it may be formed in joined segments thereof, to form a generally cylindrical protective structure. The coil assembly 30 depicted in the foregoing embodiments, is wound around the chamber 12, preferably outside of the window 60. Covering the coil assembly 30 on the outside thereof is a conductive metal enclosure 61, which forms a sealed cavity 62, which isolates the coil assembly 30 and also prevents electromagnetic energy from radiating from the coil assembly 30 and from within the chamber 12 to the outside of the chamber 12. The cavity 62 may be sealed from the chamber 11 but may be in communication with the outside atmosphere or it may be filled with an inert gas, at atmospheric or low pressure, such that formation of a plasma is not supported by the gas in the cavity 62 when the coil assembly 30 is energized.

While the window 60 itself is not electrically conductive, it is susceptible to the accumulation of a coating of conductive material sputtered from the target 16. Electrical conductivity in or on the window 60 supports the induction of currents around the chamber which reduce, cancel or otherwise undermine the effectiveness of the RF coupling of energy from the coil assembly 30 to the secondary plasma 29 in the volume 26. Such conductivity of coating on the window 60, particularly in the azimuthal (circumferential) direction, that is, a direction that extends around the chamber 12, produces an inductively coupled short circuit, can negate all or much of the energy inductively coupled into the volume 26.

To prevent such buildup of conductive sputtered material on the window 60, the preferred apparatus further includes a shield array, various embodiments of which are described below.

First Embodiment

Fig. 1 illustrates a slit cylindrical shield 100 provided between the space 11 and the window 60, in close proximity to the inside surface of the window 60. The shield 100 shadows the window 60 from material sputtered from the target 16, and preferably blocks all direct line-of-sight paths between any point on the surface 21 of the target 16 and the window 60. Further according to this embodiment, the shield 100 has a longitudinal

slit 103 therein that is parallel to the axis of the chamber 12. Shields with a single or plurality of slits fashioned to interrupt circumferential currents can also be used. The slit 103 of the preferred embodiment substantially interrupts circumferential paths in the shield 100 around the chamber 12. This prevents the induction of circumferential or azimuthal currents in the shield 100.

In addition, the shield 100 has an axial extent beyond the axial extent of the coil assembly 30 that reaches substantially the full effective axial extent of the electric field from the coil assembly 30. As a result, the electrically conductive shield 100 effectively suppresses electric fields in the secondary plasma 29 that are parallel to the axis of the chamber 12, preventing such axial electric fields that would capacitively shield the coil assembly 30 from the volume 26 and thereby undermine the coupling efficiency of energy to the volume 26 from the coil assembly 30. It is preferred that the shield 100 extend axially from behind the plane of the surface 21 of the target 16 to beyond the window 60 and coil assembly 30. With this configuration, the shield 100 more effectively shorts out axial electric fields in the secondary plasma 29, thereby enhancing the inductive coupling of energy from the coil assembly 30 into the secondary plasma 29.

The preferred embodiment of the invention also produces a high coupling efficiency of energy from the coil assembly 30 into the volume 26 due to a close spacing of the shield 100 from the window 60. This spacing is maintained at a distance that is preferably not more than the mean free path of atoms or molecules in the gas or the minimum diffusion length of the secondary plasma 29 within the chamber 12. This close shield-to-window spacing is in contrast to other embodiments described below, which permit formation of plasma adjacent a window or coil protecting non-conductive structure and behind any shield structure that is provided. Avoiding plasma formation behind the window has a tendency of increasing the percentage of energy from the coil or other plasma-generating electrode into the volume through which the sputtered particles pass, thereby increasing the effective plasma and thus the ionization efficiency of the sputtered material. In the apparatus 10, it is contemplated that processing gas pressures in the range of about 5 to 50 milli-Torr will be used. The mean free path of argon gas at such pressures is from 11 mm to 1.0 mm, respectively. As a result, the preferred spacing of the shield 100 from the window 60 is approximately 1.0 to 15 mm.

On the other hand, the slit 103 is preferably made greater than approximately 15 mm in width. The width of the slit 103 is sufficiently wide to allow the secondary plasma 29 to form in the slit 103 in order to clean sputtered material that might deposit on the edges of the shield 100 adjacent the slit 103, or on the window 60 as a result of sputtered material that passes through the slit 103. Such plasma 29 that forms in the slit 103 will extend against the window 60 in the vicinity of the slit 103 and continuously remove, by resputtering the material that deposits on the window 60 at the slit 103.

In lieu of a window 60, the coil assembly 30 may be alternatively embedded in an insulation block 66 within the chamber 12, as illustrated in **Fig. 1A**, where the insulation block 66 functions in a manner similar to that of the window 60 to isolate the coil assembly 30 from the plasma in the chamber 11 and from sputtered material. The shield 100 is configured relative to the insulation 66 in the same way it is configured relative to the window 60, in **Fig. 1**.

Many of the details of this first embodiment are useful with the embodiments described below, but have been omitted from the descriptions for simplicity, so that the differences among the embodiments can be emphasized.

Second Embodiment

Fig. 3 illustrates a shield array 200, which is an alternative to shield 100 of Fig. 1, but is provided between the space 11 and the window 60 in less close proximity to the inside surface of the window 60. The shield array 200 at least partially shadows the window 60 from material sputtered from the target 16, but has sufficient spaces or gaps 204 therein to facilitate the coupling of energy from the coil assembly 30 into the volume 26.

The shield array 200 is preferably a plurality of individual shields or shield segments 202 that shadow at least axial strips of the window 60 so that circumferential conductive paths are not formed by a coating of sputtered material. The gaps 204 are configured to substantially interrupt circumferential current paths in the shield array 200 and are configured to extend entirely or partially across the axial dimension of the array 200. The shield segments 202 should be made of a metal or other material selected to retain sputtered material coating thereon when such coating forms on the shield segments 202. Otherwise, such deposits will flake off and cause contamination of the chamber 12 and of wafers 15 being processed. In order to control the build-up of deposited material on the shield segments 202 and thereby reduce the risk of contamination, the shield segments 202 may be electrically biased. The segments 202 are also preferably individually biased with their biases separately controllable for use in optimizing the distribution of film being deposited on the substrate, such as by optimizing the uniformity of coating on, and the directionality of ionized material onto, the substrate 15. In such a configuration, the gaps 204 will completely separate and electrically isolate each of the separately biased shield segments 202 from each other. The bias is provided by a generator 206 that is connected through a filter or matching network 207, with each shield separately connected through a current limiting resistor 208. The resistors 208 may be variable or other means may be provided for individually controlling the bias of the shield segments 202 in response to the controller 50.

Fig. 5 illustrates an alternative embodiment 10a to the apparatus 10, in which a coil assembly 30 is situated in the vacuum chamber 12, inside the wall of the chamber 12 but still outside of the space 11. The protective structure is in the form of a window 60a that is situated between the coil assembly 30 and the space 11, on an enclosure 61a that extends inwardly from the inside of the wall of the chamber 12 and encloses the coil assembly 30. The enclosure 61a contains ports 62 that vent the inside of the enclosure in which the coil assembly 30 lies to the vacuum of the chamber 12. The shield array 200 is situated as in the embodiment above to shadow the window 60a from the target 16.

In lieu of a window 60 or 60a, alternative embodiment 10b of **Fig. 6** utilizes a protective structure in the form of an insulative coating 86 to cover the conductor of the coil assembly 30. In this embodiment, the coil assembly 30 is situated in the chamber 12 outside of the space 11, surrounding the volume 26. The shield array 200 is situated as in the embodiments above to shadow the insulating layer 86 from the target 16. The insulator 86 may be in any one of a number of forms, such as that of a solid insulator 86a that totally covers the surface of the conductor of the coil assembly 30, as illustrated in **Fig. 7A**, or may be in the form of a plurality of discrete insulator segments 86b, as illustrated in **Fig. 7B**. With the segmented insulator 86b, gaps 87 between the segments facilitate the effectiveness of the coil assembly 30 while the narrowness of the gaps 87 is preferably maintained to less than the mean free path of the gas molecules in the chamber 12 so that it will not communicate plasma to the conductor of the coil assembly 30. In lieu of an insulative coating on the

coil assembly 30, insulating material may encase the coil assembly 30, such as insulators 86c and 86d of **Figs. 7C** and **7D**, respectively. These features and a number of other alternative shields and protective structures for isolating the coil assembly 30 from the plasmas are useable in connection with the other embodiments.

Third Embodiment

Fig. 8 illustrates a shield array 300 provided between the space 11 and the window 60, in close proximity to the inside surface of the window 60. The shield array 300 shadows the window 60 from material sputtered from the target 16, and preferably blocks all direct line-of-sight paths between any point on the surface 21 of the target 16 and the window 60. Nonetheless, according to this embodiment of the present invention, the shield array 300 provides spaces or gaps 305 therein that provide a substantially uninterrupted area between the coil assembly 30 behind the window 60 and the volume 26 into which the plasma 29 is to be coupled, thereby facilitating the coupling of energy from the coil assembly 30 and the propagating plasma, into the volume 26.

The shield array 300 is preferably in the form of a plurality of shields or shield segments 302 that collectively shadow the window 60 from every point on the target 16. This shadowing eliminates most of the tendency for a build-up of sputtered film to form on the window 60. Accordingly, neither conductive paths nor electrostatic shielding occurs.

In one preferred embodiment of the invention, the shield segments 302 are frusto conical in shape, with the insides thereof forming an angle θ with a plane parallel to the surface 21 of the target 16 and to the substrate 15 on the support 14. The angles θ of each shield segment 302 may be the same, but the effectiveness of the shield segments 302 can be enhanced or optimized by decreasing the angles θ as the distance between the segments 302 and the target 16 increases, so that the top surface 303 of the segment 302 directly faces the target 16, providing maximum shadowing of the target 16 from the window 60 for a given segment area. The shield segments 302 lie outside of the space 11 and circumferentially surround the space 11, and are axially-spaced from each other by the circumferential gaps or spaces 305. The maximum widths of the gaps 305 are the widest gaps S that still completely shadow the surface of the target 16 from the window 60, as illustrated by lines 79, so that circumferential bands of window 60 are not exposed to the target 16 so as to deposit an annular conductive strip around the window 60. Therefore, the maximum width S of the gaps 305 can be greater at greater distances from the target 16. The gaps 305 may be narrower, but should not be less than the mean free path of atoms of the process gas at the temperature and pressure of the chamber 12, and should be optimally spaced, given the process conditions, to facilitate the most efficient diffusion of the RF plasma into the volume 26. For the same reasons, the segments 302 each have heights H that may be the same for each segment 302 or varied to optimize the shadowing and spaces between the segments 302.

The ideal number of the shield segments 302 is dependent on the geometry of the chamber 12. While a single shield segment 302 can be used, typically two to six segments 302 will be employed. The number of segments 302 should be limited and the cumulative shield segment area should be minimized to minimize RF plasma losses. Furthermore, to prevent the formation of closed circumferential paths for eddy or other currents induced by the RF coil assembly 30, the segments 302 should have at least one gap 304 interrupting each of them. The gaps 304 of the adjacent segments 302 may be in line as shown, or preferably may be staggered to prevent the deposition of a continuous line of film axially across the window 60. The gaps 304 should be

sufficiently wide to prevent arcing, which, depending on the process parameters, will require widths of about 1/4th to 1 inch.

The gaps 304 are configured to substantially interrupt current paths in the shield array 300 and are configured to extend entirely or partially across the axial dimension of the array 300. The shields segments 302 may be made of a metal, a vacuum-compatible dielectric material such as a ceramic or quartz, or some other compatible material selected to retain sputtered material coating thereon when such coating forms on the shields segments 302. Otherwise, such deposits will flake off and cause contamination of the chamber 12 and of wafers 15 being processed. In order to control the build-up of deposited material on the shield array 300 and thereby reduce the risk of contamination, the shield segments 300 may be electrically-biased, and made of metal for that purpose. The shield segments 302 are also preferably individually-biased with their biases separately controllable for use in optimizing the distribution of film being deposited on the substrate, such as by optimizing the uniformity of coating on, and the directionality of ionized material onto, the substrate 15. In such a configuration, the gaps 304 will completely separate and electrically isolate each of the separately-biased shield segments 302 from each other. The bias is provided by a generator 306 that is connected through a filter or matching network 307, with each shield segment 302 separately connected through a current limiting resistor 308. The resistors 308 may be variable or other means may be provided for individually controlling the bias of the shield segments 302 in response to the controller 50.

Advantages of the shield array 300, described above, may be realized by an alternative embodiment having a shield array 300a, as illustrated in **Figs. 9 and 10**. The array 300a is formed of a plurality of flat or slightly curved rectangular segments 302a that are arranged as an array of blades or vanes around the perimeter of the space 11 inside of the window 60. The segments 302a are circumferentially spaced from each other by axial spaces or slots 304a, which provide space between the segments 302a for plasma to couple into the volume 26 as well as interrupt potential circumferential current paths around the array 300a. The orientation of the segments 302a is such that they each define an angle ϕ with a radial plane 311 through axis 312 of chamber 12. The spacing W between adjacent ones of the shield segments 302a and between the shield segments 302a and the window 60 should not be less than the mean free path of the gas in the chamber 12 so that plasma can effectively form adjacent the window 60 and propagate into the volume 26 in the gaps 304a between the segments 302a. The segments 302a are sufficiently long in the axial direction as to prevent any circumferential band of coating to form on the window 60 at the ends of the segments 302a, and are preferably set at angle ϕ and spaces W relative to each other to shadow the entire target 16 at the window 60.

In lieu of a window 60 the shield arrays described above may be used with a dielectric window provided inside of the chamber or with a coil in the chamber that is protected from the plasmas by insulation.

* * *

Those skilled in the art will appreciate that the implementation of the present invention herein can be varied, and that the invention is described in preferred embodiments. Accordingly, additions and modifications can be made, and details of various embodiments can be interchanged, without departing from the principles and intentions of the invention. What is claimed is:

1. An ionized physical deposition method comprising the steps of:

creating, with a main energy source, a main plasma in a vacuum chamber and sputtering a target therewith to produce particles of coating material in a space between the target and a substrate to be coated;

with a coil surrounding the space and through a dielectric material interposed between the coil and the space, inductively coupling RF energy from the coil through the dielectric material and into a volume of the space between the substrate and the main plasma to energize with the coupled RF energy a secondary plasma in the volume and ionizing particles of the coating material in the volume with the secondary plasma;

while the main plasma creating step is being performed and with a shield spaced from the dielectric material and positioned between the space and the dielectric material, physically shielding the dielectric material from particles of coating material without electrically shielding the volume from the RF energy; and

electrically directing ionized particles of coating material from the volume onto the substrate.

2. The method of claim 1 further comprising the step of:

biasing the shield to control substrate contamination from film forming on the shield array.

3. The method of claim 1 further comprising the step of:

biasing the shield to control the distribution of film being deposited on the substrate.

4. The method of claim 3 wherein:

the biasing step includes the step of individually and selectively biasing a plurality of electrically distinct sections of the shield to control the distribution of film being deposited on the substrate.

5. The method of claim 1 wherein:

the coupling step is performed through a dielectric window in a wall of the vacuum chamber.

6. The method of claim 1 wherein:

the coupling step is performed with the coil positioned outside of the chamber and through a dielectric window in a wall of the vacuum chamber.

7. The method of claim 1 wherein:

the coupling step is performed with the coil positioned inside the chamber and through a dielectric window inside the chamber.

8. The method of claim 1 wherein:

the coupling step is performed with the coil inside of the chamber having the dielectric material coating the coil.

9. The method of claim 1 wherein:

the ionized particle electrically directing step includes the step of biasing the substrate to attract ionized particles of coating material from the volume onto the substrate.

10. An ionized physical vapor deposition apparatus comprising:

a vacuum sputtering chamber;

a sputtering target in the chamber having a sputtering surface thereon;

a cathode power supply connected to the target to energize the target to produce a main plasma in proximity to the sputtering surface;

a substrate support in the chamber spaced from the target, oriented to support a substrate thereon facing the target and parallel thereto, and defining a space between the target and the substrate holder;

a coil surrounding a volume of the chamber between the main plasma and the substrate holder;

an RF energy source connected to the coil to energize the coil to inductively couple RF energy into the volume to form a secondary plasma to ionize in-flight sputtered material passing through the volume;

means for electrically directing ions of the sputtered material in a direction normal to the substrate;

electrically non-conductive protective structure interposed between the coil and the space to isolate the coil from plasma in the space; and

a shield disposed circumferentially around and outside of the space, inside the vacuum chamber and spaced inwardly from the electrically non-conductive protective structure between the target and the electrically non-conductive protective structure so as to physically shield the electrically non-conductive protective structure from sputtered material, the shield having at least one axially extending gap at least partially electrically separating the shield sufficiently to reduce circumferential currents in the shield.

11. The apparatus of claim **10** wherein:

the shield includes an array of a plurality of distinct shield segments spaced by gaps which electrically separate the segments.

12. The apparatus of claim **10** wherein:

the electrically non-conductive protective structure includes a dielectric window in a wall of the chamber, the coil being located behind the window outside of the chamber.

13. The apparatus of claim **10** wherein:

the coil is positioned inside of the chamber; and

the electrically non-conductive protective structure includes a dielectric window inside the chamber between the coil and the space.

14. The apparatus of claim **10** wherein:

the coil is positioned inside the chamber; and

the electrically non-conductive protective structure includes an insulation layer on the coil.

15. The apparatus of claim 14 wherein:

the insulation layer completely covers the coil.

16. The apparatus of claim 14 wherein:

the insulation layer includes a plurality of discrete insulation segments separated by gaps having insufficient widths to support penetration of plasma through the gaps to the coil.

17. The apparatus of claim 10 wherein:

the RF energy source is operative to energize the coil at a frequency of between 0.1 MHz and 60 MHz.

18. The apparatus of claim 10 further comprising:

means for electrically biasing the shield.

19. The apparatus of claim 10 wherein:

the shield includes an array of a plurality of distinct shield segments spaced by of gaps electrically separating the segments; and

the apparatus further comprises means for electrically biasing the shield segments of the array.

20. The apparatus of claim 10 wherein:

the means for directing ions of sputtered material includes a bias energy generator connected to the support to electrically bias a substrate on the support to accelerate ions of the sputtered material in a direction normal to the substrate.

21. An ionized physical deposition method comprising the steps of:

producing a main plasma in a vacuum chamber with a main energy source;

sputtering a target of electrically conductive coating material with the main plasma in the vacuum chamber and producing thereby sputtered particles of electrically conductive coating material in a space between the target and a substrate to be coated which is supported in the chamber;

inductively coupling RF energy from a coil surrounding the space through a dielectric window between the coil and the space and forming with the coupled RF energy a secondary plasma in a volume of the space that lies between the substrate and the target;

ionizing sputtered particles of the coating material in the volume with the secondary plasma;

physically shielding the dielectric window from the sputtered particles of electrically conductive coating material with a shield, in the vacuum chamber and spaced inwardly from the window, such that, if the shield is coated with the electrically conductive coating material it allows passage of RF energy from the coil into the volume; and

directing ionized particles of the coating material from the volume toward the substrate.

22. The method of claim 21 wherein:

the ionized particle directing step includes the step of electrically biasing the substrate and thereby electrostatically attracting ionized particles of coating material shielding toward the substrate.

23. The method of claim 21 wherein:

the shielding step is performed with a shield that provides no circumferential current path around the space.

24. An ionized physical vapor deposition apparatus comprising:

a vacuum sputtering chamber having opposite ends and a sidewall extending around the chamber between the ends, the sidewall having a dielectric window therein extending around the chamber;

a sputtering target centered on an axis in the chamber at one end thereof and having a sputtering surface thereon;

separately operable power supplies including (a) a cathode power supply for energizing a main plasma for ionizing gas in the chamber to produce ions of the gas to sputter the target sputter material from the sputtering surface of the target and (b) an RF energy source for producing a secondary for ionizing material after it has been sputtered from sputtering surface of the target;

the cathode power supply being connected to the target to energize the target to produce the main plasma in close proximity to the sputtering surface;

a substrate support in the chamber at the end thereof opposite the target and spaced from the target to support a substrate parallel to the target;

a coil outside of the chamber and surrounding the dielectric window opposite a volume of the chamber between the main plasma and the substrate holder;

the RF energy source being connected to the coil to energize the coil to inductively couple RF energy through the window to the secondary plasma in the volume to ionize in-flight sputtered material when passing therethrough; and

a shield encircling the chamber outside of the volume and formed of at least one inclined shield segment inside of and spaced from the window, each segment having a surface facing the target and inclined at an angle to the sputtering surface of the target and to the axis of the target to shadow substantially all points on the window from the sputtering surface of the target , the shield having at least one gap therein that interrupts circumferential current paths around the chamber and the shield being configured to facilitate the extension of the secondary plasma from adjacent the window into the volume.

25. The apparatus of claim 24 wherein:

the shield includes a plurality of distinct shield segments.

26. The apparatus of claim 24 further comprising:

a bias potential generator connected to the support to electrically bias a substrate on the support to accelerate ions of the sputtered material in a direction normal to the substrate.

27. The apparatus of claim **24** wherein:

the shield includes a plurality of axially spaced frusto-conical shield segments.

28. The apparatus of claim **24** wherein:

the shield includes a plurality of circumferentially spaced blade-like shield sections having axially extending spaces there between.

29. The apparatus of claim **24** wherein:

the coil is a helical coil positioned surrounding the chamber.

30. The apparatus of claim **24** wherein:

the shield array is biased.

31. An ionized physical vapor deposition apparatus comprising:

a vacuum sputtering chamber having a dielectric window therein extending around the chamber, a sputtering target therein centered on an axis at one end thereof and a substrate support therein for supporting a substrate parallel to the target on the axis at an opposite end thereof;

separately operable power supplies including (a) a cathode power supply for energizing a main plasma for ionizing gas in the chamber to produce ions of the gas to sputter the target sputter material from the sputtering surface of the target and (b) an RF energy source for producing a secondary for ionizing material after it has been sputtered from sputtering surface of the target;

the cathode power supply being connected to the target to energize the target to produce the main plasma in close proximity to the target;

an RF coil surrounding the chamber outside of the dielectric window positioned to inductively couple RF energy from the RF energy source into the chamber to form the secondary plasma in a volume of the chamber between the main plasma and the substrate holder; and

a shield encircling the chamber between the volume and the window, the shield formed of a plurality of frusto-conical sections inclined so as to generally face the target and spaced from each other so as to generally shadow substantially all points on the window from the target, the segments each having at least one axial gap therein to interrupt circumferential current paths around the chamber, the segments being spaced axially from each other to define space from the window into the volume effective to facilitate extension of the secondary plasma through the spaces from the window into the volume.

32. An ionized physical vapor deposition apparatus comprising:

a vacuum sputtering chamber having a dielectric window therein extending around the chamber, a sputtering target therein at one end thereof and a substrate support therein for supporting a substrate parallel to the target at an opposite end thereof;

separately operable power supplies including (a) a cathode power supply for energizing a main plasma for ionizing gas in the chamber to produce ions of the gas to sputter the target sputter material from the sputtering surface of the target and (b) an RF energy source for producing a secondary for ionizing material after it has been sputtered from sputtering surface of the target;

the cathode power supply being connected to the target to energize the target to produce the main plasma in close proximity to the target;

an RF coil surrounding the chamber outside of the dielectric window positioned to inductively couple RF energy from the RF energy source to form the secondary plasma in a volume of the chamber between the main plasma and the substrate holder; and

a shield encircling the chamber between the volume and the window, the shield formed of a plurality of axially extending blades circumferentially spaced from each other around the volume, each blade being inclined at an angle relative to a radial plane through the blade and through the central axis of the chamber, the blades being oriented and spaced from each other so as to generally shadow substantially all points on the window from the target, the blades each being spaced from each other to define space from the window into the volume effective to facilitate the extension of the secondary plasma into the volume.

33. The apparatus of claim 32 further comprising:

a bias potential generator connected to the support to electrically bias a substrate on the support to accelerate ions of the sputtered material in a direction normal to the substrate.

34. The apparatus of claim 31 further comprising:

a bias potential generator connected to the support to electrically bias a substrate on the support to accelerate ions of the sputtered material in a direction normal to the substrate.

35. An ionized physical vapor deposition apparatus comprising:

a vacuum chamber having a processing gas space enclosed therein to be maintained at a low pressure level;

a source of vapor deposition material at one end of the chamber;

a substrate support in the chamber at an end thereof opposite the source of vapor deposition material and facing the same to support a substrate thereon parallel to the source;

at least one coil surrounding the chamber between the substrate support and the surface of the source;

the chamber including a window between the coil and the space to isolate the coil from the process gas in the space;

an RF energy source connected to the coil and operative to energize the coil to inductively couple RF energy through the window to energize a secondary plasma in the gas in the space; and

a metallic shield encircling the chamber inside of the window and in close proximity thereto, the shield extending axially sufficiently far to shadow the window from the source of material and to electrically short out substantially all axial electric field in the plasma, the shield having at least one axial slit therein extending the axial length thereof to interrupt circumferential conductive paths in the shield around the chamber.

36. The apparatus of claim 35 wherein:

the at least one coil has a center tap and the RF energy source is connected to the center tap.

37. The apparatus of claim 35 further comprising:

a bias potential generator connected to the support to electrically bias a substrate on the support to accelerate ions of the deposition material in a direction normal to the substrate.

38. The apparatus of claim 35 further comprising:

a magnet surrounding the chamber having a magnetic field that is oriented axially in the space within the chamber.

39. The apparatus of claim 35 further comprising:

means for generating a magnetic field that is oriented axially in the space within the chamber.

40. The apparatus of claim 35 wherein:

the at least one slit in the shield is sufficiently wider than the mean free path of atoms of the gas in the chamber to permit the formation of plasma in the slit.

41. The apparatus of claim 35 wherein:

the shield has a height that is at least the axial length of the coil.

42. The apparatus of claim 35 wherein:

the coil is a helical coil positioned surrounding the chamber.

43. The apparatus of claim 35 wherein:

the window is a generally cylindrical window formed of an electrically non-conductive material forming part of an inner wall of the chamber and in contact with the process gas on the inside thereof.

44. The apparatus of claim 35 wherein:

the window is in the form of an electrically non-conductive material encasing the coil and situated to be in contact on at least one side thereof with the process gas.

45. An ionized physical vapor deposition apparatus comprising:

a vacuum chamber having a processing gas space enclosed therein to be maintained at a low pressure level;

a sputtering target at one end of the chamber;

a substrate support in the chamber at an end thereof opposite the target and facing the target to support a substrate thereon parallel to the target;

at least one coil surrounding the chamber between the substrate support and the surface of the target;

the chamber including a window between the coil and the space to isolate the coil from the process gas in the space;

an RF energy source connected to the coil and operative to energize the coil to inductively couple RF energy through the window to energize a secondary plasma in the gas in the space; and

a metallic shield encircling the chamber inside of the window and in close proximity thereto, the shield extending axially sufficiently far to shadow the window from material sputtered from the target and to electrically short out substantially all axial electric field in the plasma, the shield having at least one axial slit therein extending the axial length thereof to interrupt circumferential conductive paths in the shield around the chamber.

46. The apparatus of claim 45 wherein:

the spacing between the shield and the window is not more than the mean free path of atoms of gas in the vacuum of the space in the chamber so as to avoid plasma formation behind the shield.

47. The apparatus of claim 45 further comprising:

a bias potential generator connected to the support to electrically bias a substrate on the support to accelerate ions of the sputtered material in a direction normal to the substrate.

48. The apparatus of claim 45 further comprising:

a magnet surrounding the chamber having a magnetic field that is oriented axially in the space within the chamber.

49. The apparatus of claim 45 further comprising:

means for generating a magnetic field that is oriented axially in the space within the chamber.

50. The apparatus of claim **45** wherein:

the slit in the shield is sufficiently wider than the mean free path of atoms of the gas in the chamber to permit the formation of plasma in the slit.

51. The apparatus of claim **45** wherein:

the shield has a height that is at least the axial length of the coil.

52. The apparatus of claim **45** wherein:

the coil is a helical coil positioned surrounding the chamber.

53. The apparatus of claim **45** wherein:

the window is a generally cylindrical window formed of an electrically non-conductive material forming part of an inner wall of the chamber and in contact with the process gas on the inside thereof.

54. The apparatus of claim **45** wherein:

the window is in the form of an electrically non-conductive material encasing the coil and situated to be in contact on at least one side thereof with the process gas.

55. A method of ionized physical vapor deposition comprising the steps of:

providing a vacuum chamber having a processing gas space enclosed therein, a source of vaporized coating material at one end of the chamber; and a substrate support in the chamber at an end thereof opposite the source and facing the source to support a substrate thereon;

inductively coupling RF energy into the chamber with a coil surrounding the chamber from behind a dielectric material which isolates the coil from the process gas in the processing space;

placing an axially-extended and axially-slit metallic shield inside of the window and in close proximity thereto, shadowing the window therewith from material sputtered from the target and electrically shorting therewith substantially all axial electric field in the plasma.

56. The method of claim **55** wherein:

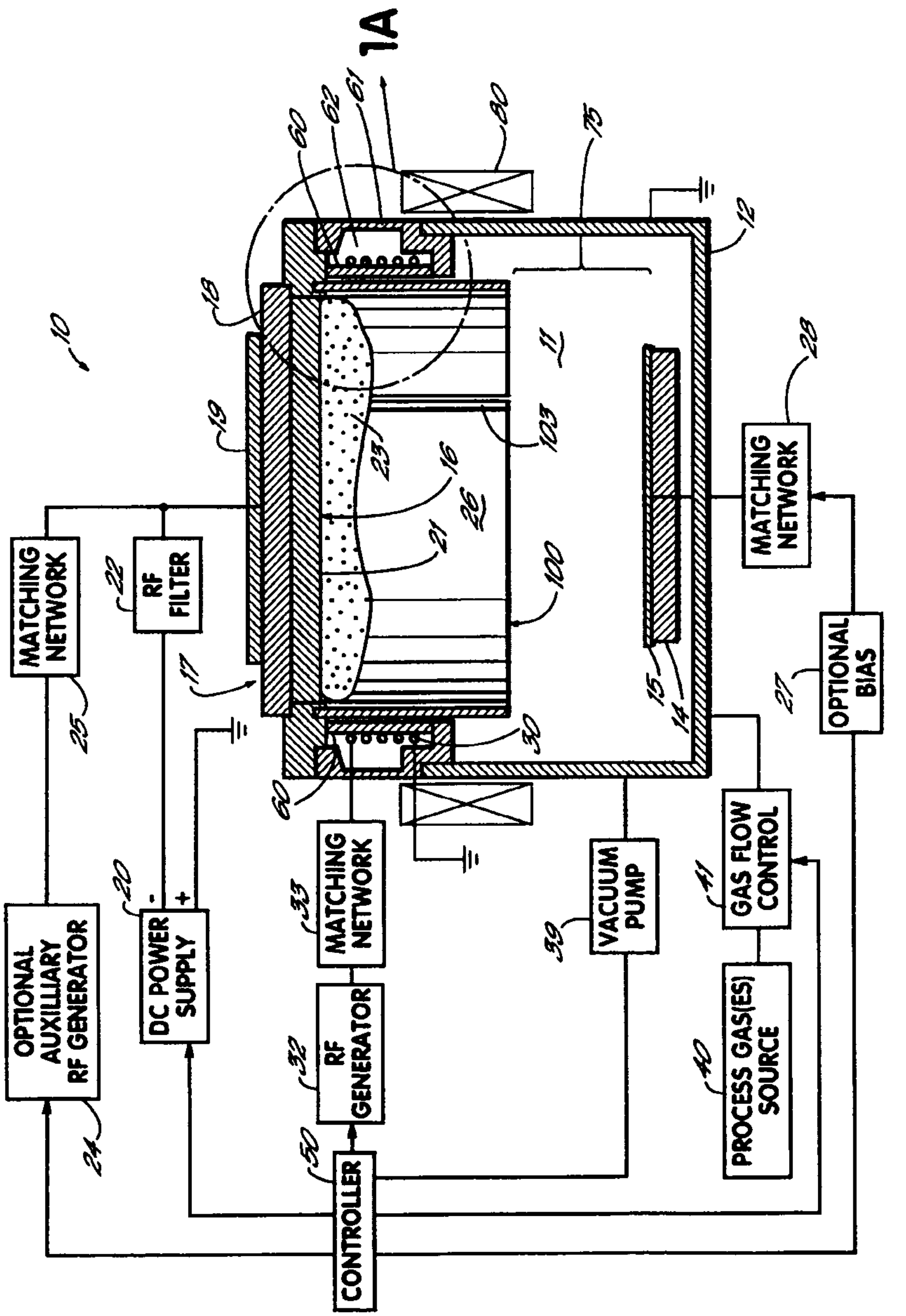
the source is a target of sputter coating material; and

the method includes the step of energizing the target and sputtering the coating material therefrom.

57. The method of claim **55** wherein:

the source is a PVD source of evaporation material; and

the method includes the step of evaporating the evaporation material into the chamber.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RF FILTER
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33
RF GENERATOR
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CONTROLLER
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VACUUM PUMP
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GAS FLOW CONTROL
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PROCESS GAS(ES) SOURCE
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OPTIONAL BIAS
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FIG. 1

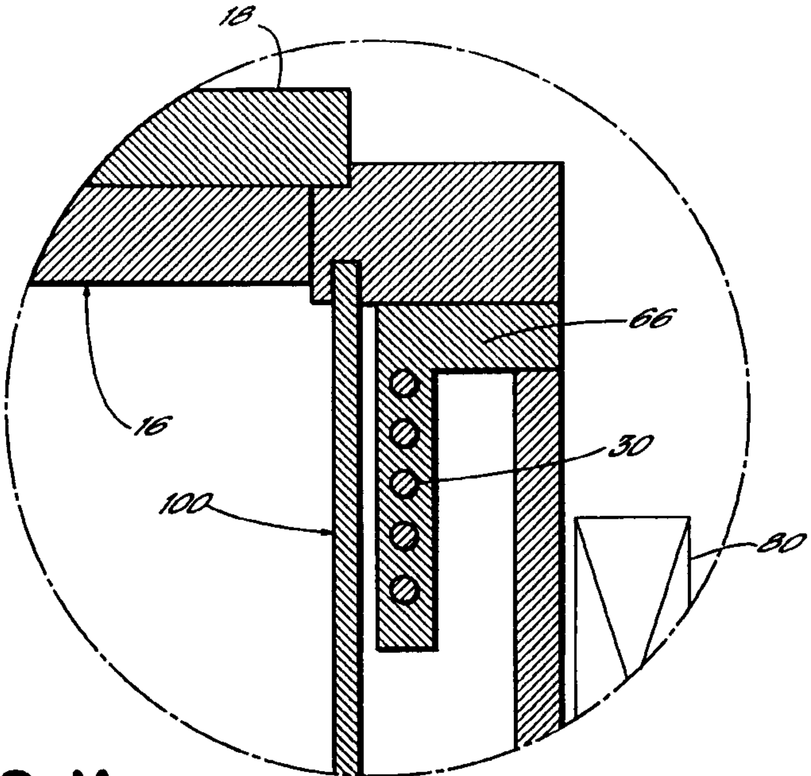


FIG. 1A

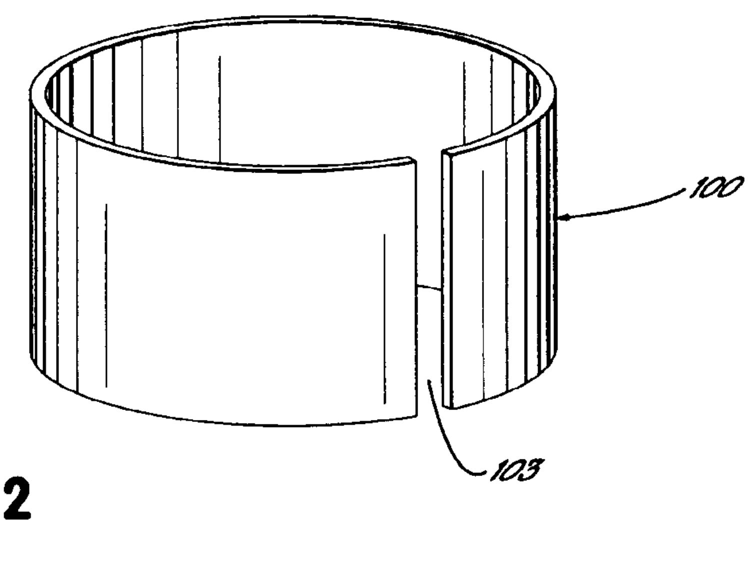


FIG. 2

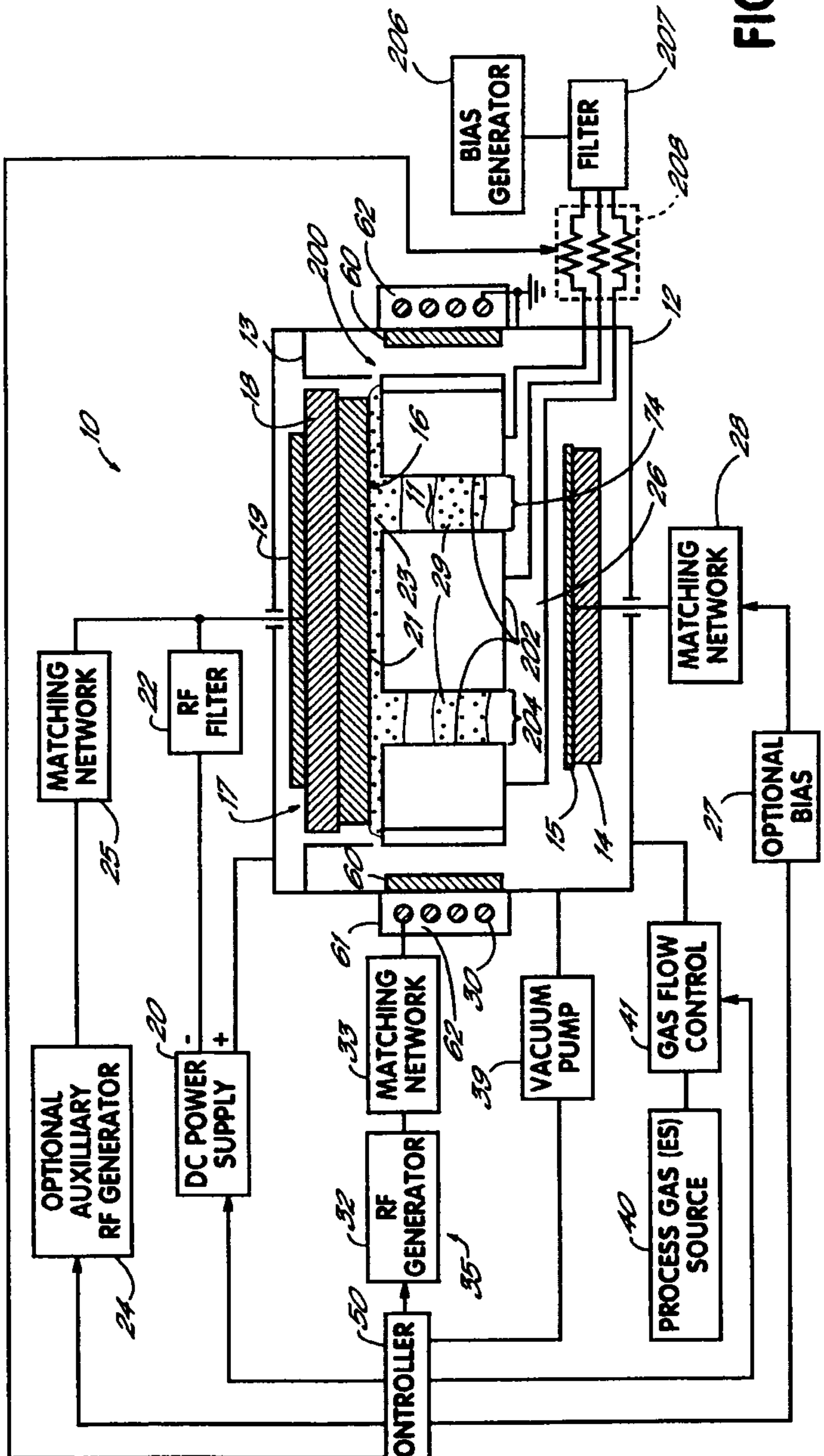


FIG. 3

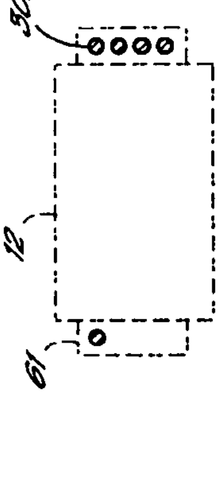


FIG. 4A

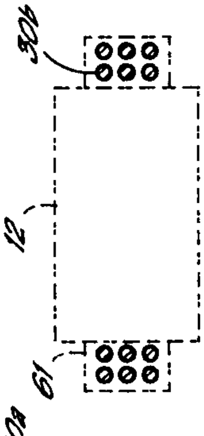


FIG. 4B

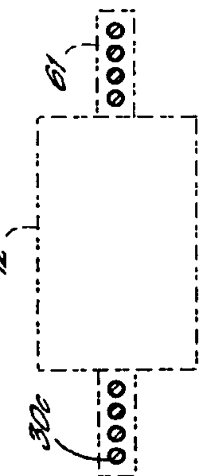


FIG. 4C

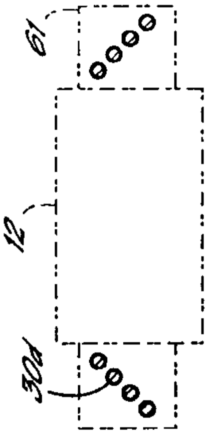


FIG. 4D

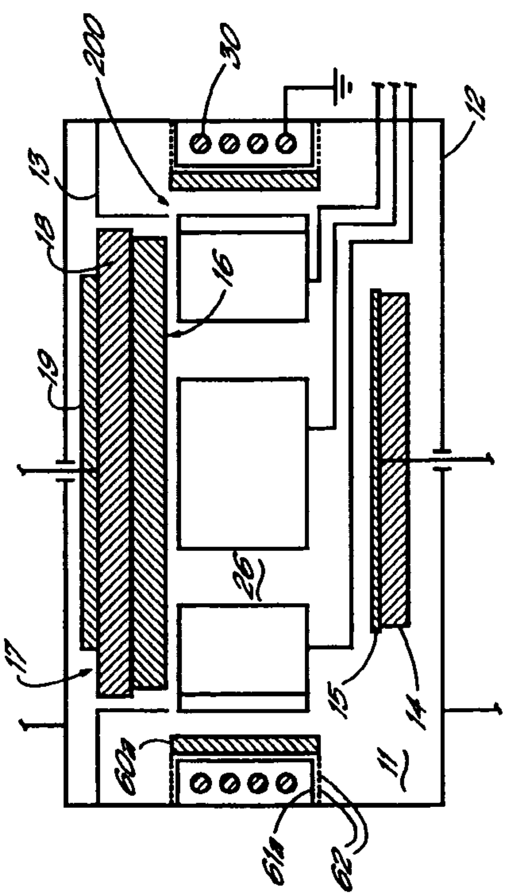


FIG. 5

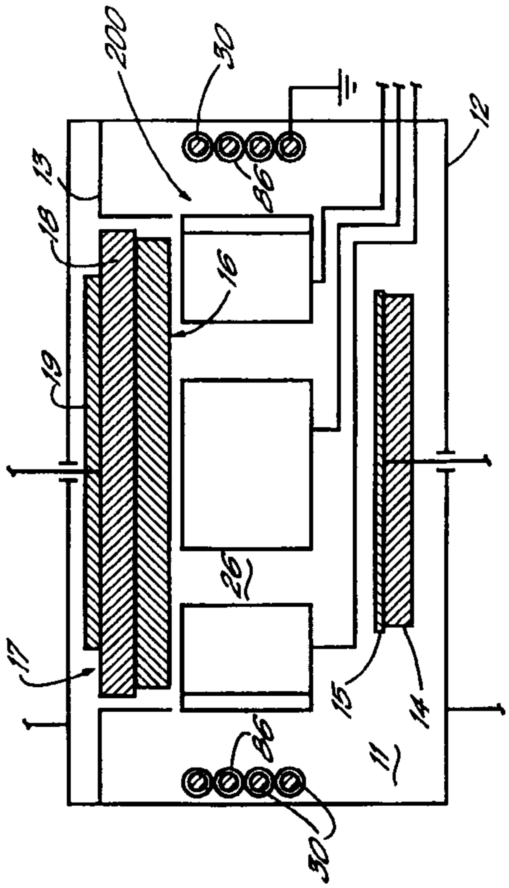


FIG. 6

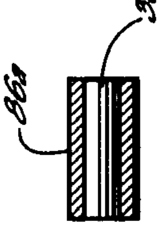


FIG. 7A

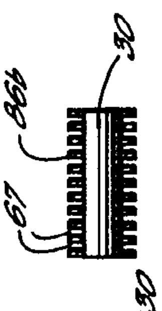


FIG. 7B

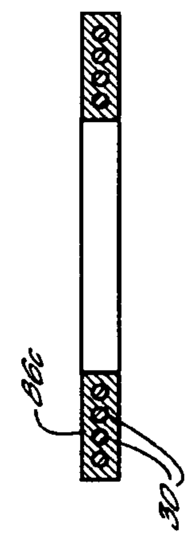


FIG. 7C

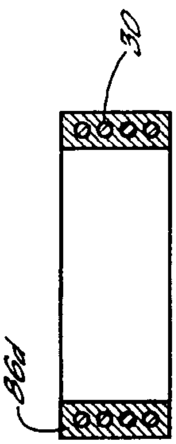
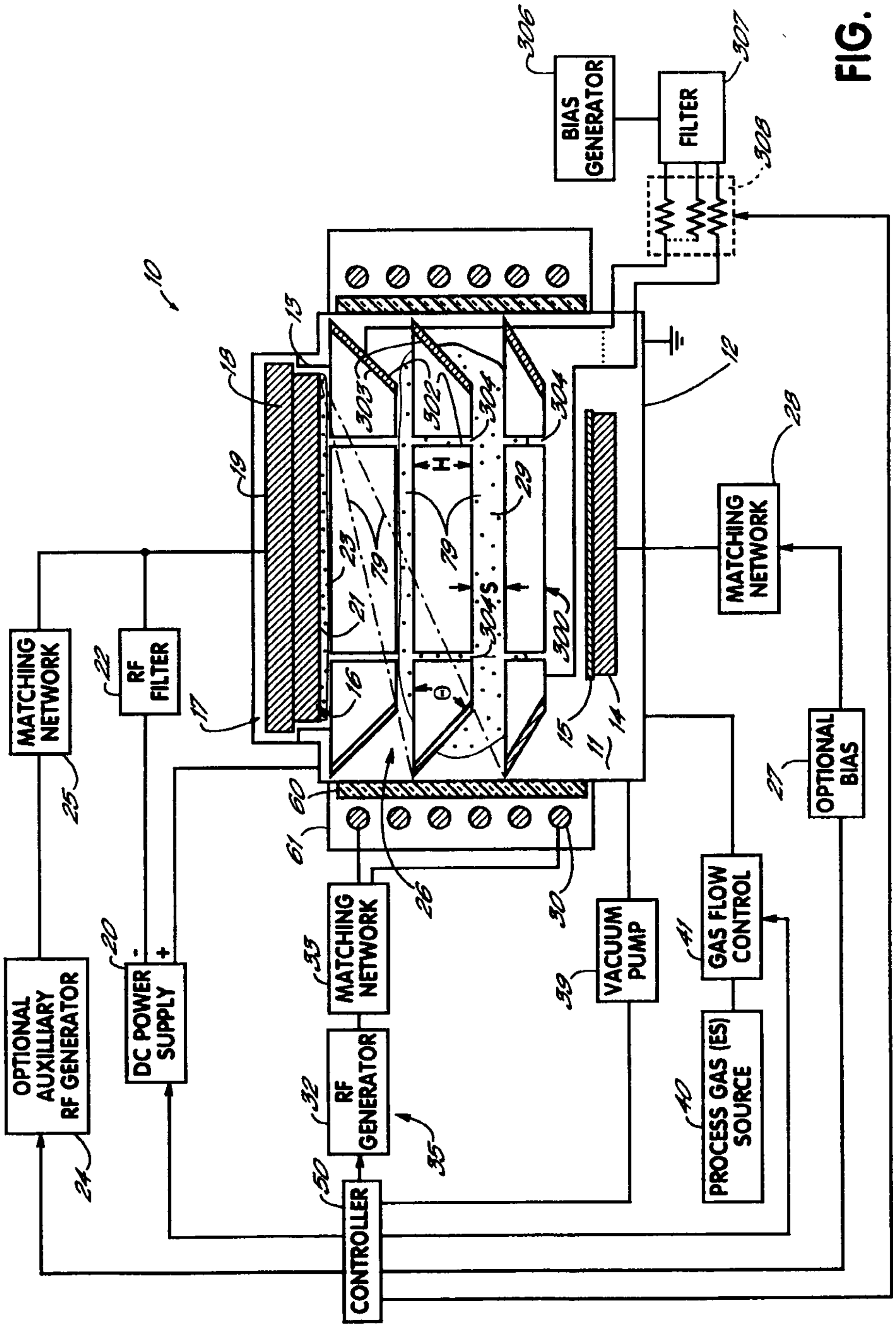


FIG. 7D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GAS FLOW CONTROL
PROCESS GAS (ES) SOURCE
OPTIONAL BIAS
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FIG. 8

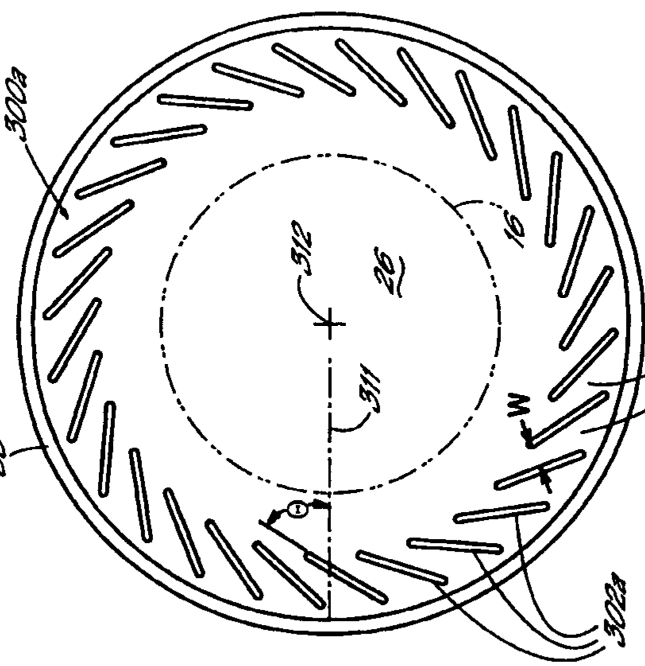
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FIG. 10

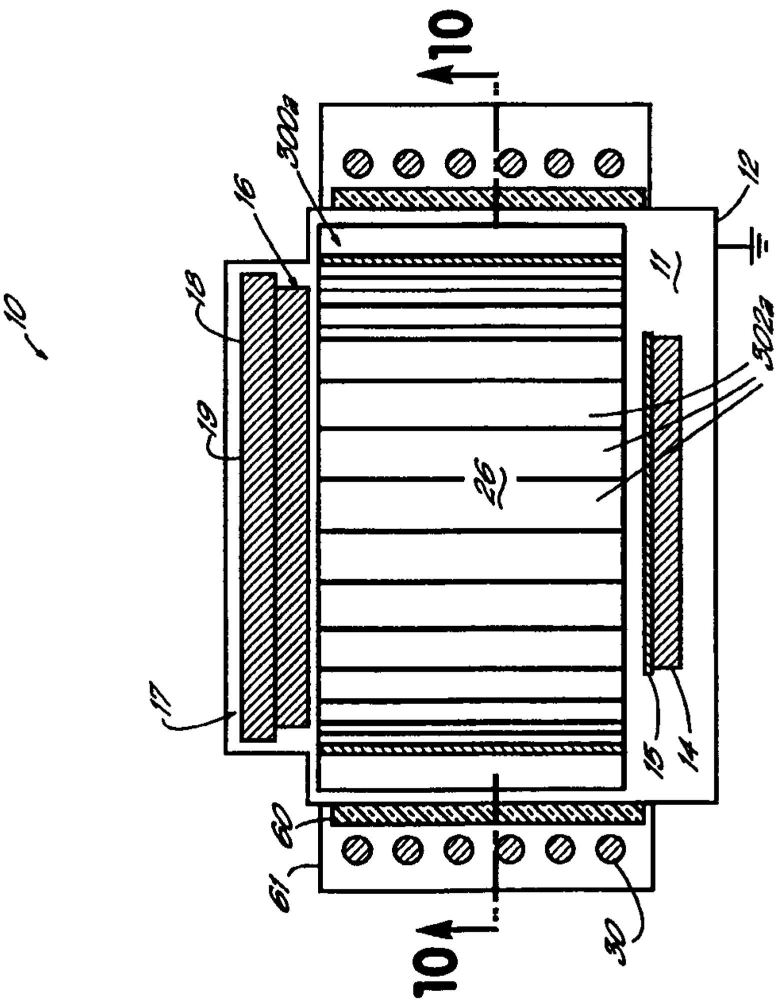
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FIG. 9

INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/US 98/08033

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01J37/34 H01J37/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 593 924 A (LEYBOLD AG) 27 April 1994	1-3,8, 21,35, 39,41-44
A	see column 2, line 35 - column 3, line 40; figure 1	10,24, 31,32, 45,55
P,X	EP 0 782 172 A (APPLIED MATERIALS INC) 2 July 1997 see the whole document	1-57
P,X	EP 0 836 218 A (APPLIED MATERIALS INC) 15 April 1998 see the whole document	1-57

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 July 1998	31/07/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schaub, G

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte. onal Application No
PCT/US 98/08033

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